Abstract

Dust transport and migration is not well understood in tokamaks. Furthermore, current numerical codes (DUSTT) have not been benchmarked with experiments. Interest in dust has increased over recent years as it may be a significant issue in machines with high duty cycles (ITER, DEMO). Measuring dust particle trajectories in the plasma can also give added information on Scrape-Off Layer (SOL) flows, since an important force on dust flow is a plasma drag force. In order to study dust particle trajectories in the SOL for different plasma densities and topologies, we have designed and installed a dust injector which injects Boron dust particles into the divertor region. The particles are viewed with a video camera. This provides us with a 2-D projection of the particle trajectories. For full 3-D trajectories we would need to install a second viewing camera. Initial data and results will be presented along with the successes and shortcomings of the diagnostic and future improvements.
The Dust Injector

- Boron injected with a ~10 psia puff of deuterium over ~0.1 s.
- Boron particles have radii between 40 and 120 μm, giving an estimated flow of ~60,000 boron dust particles per second (If all particles exit the capillary tube.)
- A 150 mW, 532 nm CW laser illuminates the particles.
- A digital camera is optically filtered to view scattered light off of the particles.
- The puffing system is installed on A-port bottom. The laser enters via B-port horizontal with a fiber feedthrough.
- We view the particles in the divertor using the div2 divertor camera.
Motivation

- Dust transport is not well understood as numerical codes have just begun being benchmarked against experiments.
- Dust buildup is an issue on reactor devices as there are site limits on how much tritiated particles can be in the vacuum vessel.
- Tracking the motion of dust particles can give information about plasma edge properties.
Flow Chart of Dust Injector

- Dust Injector has two steps to inject dust, a shaking mode and a puffing mode.
- During the shaking mode, the fast valve is closed and the gate valve is opened.
- During the puffing mode, the gate valve is closed and the fast valve is opened with a pneumatic control.
- After a puff, the fast valve is closed and the gate valve is reopened to pump out the gas in the volumes of the funnel and the hand valve.
- The hand valve is specially designed ball valve. It is designed to maintain a high vacuum seal in a dusty environment. It is closed to isolate the system from C-Mod in order to refill the Boron Shaker, or to prevent boron from leaking into the cell through our vacuum pump during a boronization.
The saltshaker was designed by J. Irby to deposit boron flakes through a upper vertical port.

- The solenoid is pulsed, pulling up a plug which allows particles to fall from the hopper into the piping below.
- The solenoid is driven at 100V typically at speeds between 1-30 Hz.
- Boron particles may range in size but are typically on the order of 10s of microns.
- Roughly 1 mg of boron particles are discharged per pulse at 10 Hz.
- An additional laser scattering apparatus may be attached below the boron shaker to ensure particles are being dropped.

Picture courtesy of J. Irby APS Oct 28, 2003
Above is a picture of the dust injector in the vessel taken directly before close up for the 2007-2008 campaign.
Toroidal diagram of the camera views in the C-Mod vacuum vessel.
• The Div2 camera views from A-port down into the divertor of the plasma.

• It has a good view of B-port and C-port and barely sees D-port. This covers a toroidal section of the divertor over 72°.

• The camera has a frame rate of 28.5 Hz, and integrates over a 3.7 ms time period (although this can be adjusted.) This produces a full image every 35.1 ms.
Issues With Laser Illumination

- Laser illumination requires a tradeoff between the size of the illuminated area and the intensity of the beam.
- During the last campaign (we think) that there was a misalignment between the laser beam and the dust particle trajectory.
- Boron coating and damage to collimator dropped power transmission through the collimator by a factor of 2/3.
- Laser would sometimes mysteriously turn off in the middle of a plasma shot.

The collimator on the right was the one used in vessel during the past campaign. It shows significant damage due to boron coating and other permanent damage. On the left is an unused collimator for comparison.
Boron Dust Injections

Above are two frames from a typical dust injection. In the first frame a plume of dust can be seen, this frame is taken shortly after the dust puff. In the second frame individual particles can be seen. This frame is about 0.1-0.4 s after the dust is puffed.
Dust Puffing in 2007 campaign

- Dust was puffed 98 times during the 2007 campaign.
- Dust was puffed into plasma 82 times, 65 of the shots had a recognizable dust particle on the Div2 camera.
- Exactly 1 disruption was caused by a dust puff (the first time it was operated.)
- Almost all operation was piggybacking. Usually it would fire late in the discharge with dust particles entering the plasma towards the end of the flattop (1.3-1.4 s)
- Boron shaker is operated between shots. There have been up to 15 dust puffs without operating the shaker and particles are still seen on the Div2 camera.
- Normal operating parameters were with plenum pressures of 10 psia and a puff duration of 0.1 s
- Average amount of gas through the BN valve is $\sim 7 \times 10^{20}$ molecules. Based on puffing into vacuum, we estimate that only $1-5 \times 10^{19}$ molecules actually make it into the vessel in 1 s.
- Particles were most clearly visible when lower divertor light was low (i.e. USN plasmas.)
Dust Puffing in 2007 campaign (cont.)

- A Dust puff showed virtually no affect on the bulk plasma. (either positive or negative.) Specifically, there is no measurable change in core plasma density.
- At ~0.3 s after the puff a plume is seen on the Div2 camera likely signifying the main gas puff.
- Dust particles are seen as early as 0.3 s after the puff trigger and usually continue until the end of the plasma.
- Most (all?) of these particles are not in the laser line, but rather are illuminated by reflected plasma light, or by self-radiation.
- No noticeable difference in particle behavior during normal and reversed fields.

Composite of all dust particles as seen by Div2 superimposed on a background image during 1070627 (19 shots)
Stereoscopic Imagining Overview

- In order to determine the 3D position of a particle, you need (at least) two separate cameras.
- The relation between a position in 3-space and the pixel location on the camera is given by:

\[ \delta = \alpha_1 \tan(\theta) + \alpha_2 \tan^2(\theta) + \ldots \]

- Accordingly, you need to know 7+ independent parameters for each camera. The XYZ location of the camera, the orientation of the center-line, the magnifications factors \( \alpha_n \) and an arbitrary rotation angle.
- From an image on the camera you can pick out the line in 3-space that the particle must be on. Finding where lines from two separate cameras intersect gives the location of the particle in 3-space.
- Special thanks to B. Bose for helping with this, and giving me ideas on how to apply it to my system.
In this past campaign the two cameras that were used were Div2 and Jant. These cameras are ill-suited for stereoscopic imaging.

- We obtained the XYZ camera location from CAD drawings.
- To get the other parameters, we made a best fit using structures in the image of known location. (tile corners, also from CAD drawings)

The above graph shows the results from calibrating the Jant camera using tile corners. The plus signs show where the tile corners appear on the pixel array. The stars are where they should appear based on their 3-D locations. The error is about 1-2 pixels per corner which is about the error in pixel selection.
Stereoscopic Imagining: Interesting Object

View from Div2 camera

View from Jant camera
Where is the Object?

- The object on the above slide appeared during the early part of the plasma (0.175 s) when the plasma was still limited.
- We surmise that the particle to the left is outside the last closed flux surface, and when it enters the plasma it gets larger and brighter and extends along a flux tube.
- The particle appeared on two separate cameras, since these cameras are very close together they are ill-suited for stereoscopic imaging. A small error in pixel selections can map to a larger error in particle location.

The plot above shows the poloidal locations of the selected areas of the object on the previous slide. Also shown is the last closed flux surface as calculated by the Efit routine.
Where is the Object? (close-up)

- Using both Jant and Div2 cameras an error of one pixel in the x-coordinate can lead to an error of 1 cm in the location in space.
- The difference in location is about 1-2 cm poloidally and 3-4 cm toroidally. The poloidal difference is not large enough to be considered accurate due to our error.
- Nevertheless it is clear that the particle lies on or near the last closed flux surface which is as expected.
- The “head” of the object and its “tail” differ by 6-10 cm toroidally.

Close-up of the poloidal locations of the particle features

![Last Closed Flux Surface and Vessel Wall](image)
Future Plans of Dust Injector

- Move capillary closer to plasma, so that the dust plume is within sight of the camera in the re-entrant tube on B-Port horizontal.
- Put Boronization “shield” on collimator, in an attempt to reduce damage to the collimator lens.
- Operate dust injector with cryopump, and experiment with longer gas puffs.
- Continue operating dust puffer in piggy-back mode
Conclusions

- The dust injector worked to specifications in the past campaign and injected dust particles reliably into the plasma with no adverse effects to plasma performance.
- Laser illumination did not work as desired in this past campaign.
- With the new camera view on B-Port, stereoscopic imaging will be possible in the next campaign allowing particles to be tracked in the SOL.

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